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FRACTURE TOUGHNESS OF CIP-HIP BERYLLIUM AT ELEVATED
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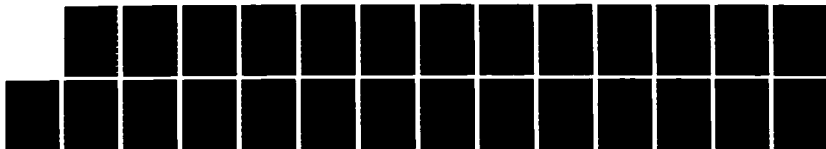
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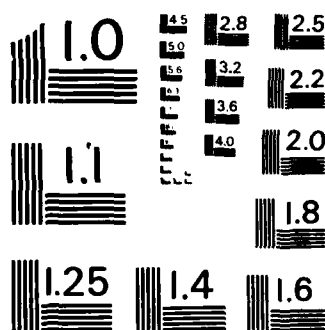
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FRACTURE TOUGHNESS OF CIP-HIP BERYLLIUM
AT ELEVATED TEMPERATURES

April 1986

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Final Report

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ABSTRACT

The fracture toughness of CIP-HIP Beryllium was determined using the short bar fracture toughness (K_{ICSB}) method. The K_{ICSB} value measured was 10.96 MPa \sqrt{m} at room temperature. This falls well within the expected range of 9 to 12 MPa \sqrt{m} as observed from previous fracture toughness measurements of beryllium. Toughness increased rapidly between 400°F and 500°F reaching a value of 16.7 MPa \sqrt{m} at 500°F.

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PREFACE

This report was prepared by Terra Tek, Inc. under the Army Materials Technology Laboratory Contract No. DAAG-46-80-C-0038. The work was administered under the direction of the Ballistic Missile Defense Materials Program Office, Army Materials Technology Laboratory, with Mr. John F. Dignam as Program Manager and Dr. S. C. Chou as Technical Monitor.

This report covers work conducted from May 13, 1980 through February 13, 1981.

TABLE OF CONTENTS

	<u>Page</u>
PREFACE	i
TABLE OF CONTENTS.....	ii
LIST OF FIGURES.....	iii
LIST OF TABLES.....	iv
INTRODUCTION.....	1
TEST METHODOLOGY.....	2
Test Specimens.....	2
Test Method.....	4
Data Analysis.....	4
Test Results.....	8
DISCUSSION OF RESULTS.....	11
REFERENCES.....	12

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
1	Short Bar Specimen.....	2
2	Short Bar Specimen Locations in the Three-Point Bend Specimen.....	3
3	Short Bar Specimen Locations in the Compact Tension Specimen.....	3
4	Fractometer Method of Loading Short Bar Specimen.....	4
5	Load Versus Mouth Opening Type Curve Observed in the Fracture Toughness Testing of Beryllium Using Short Bar Specimens.....	5
6	In (a), the flatjack's loading of the specimen and incremental crack growth Δa are depicted. In (b), a plot of the pressure-volume loading curve is shown, including the straight line reloading and unloading paths AO and BO.....	5
7	Beryllium Fracture Toughness.....	9

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
I	Individual Beryllium Fracture Toughness Measurements.....	8
II	Beryllium Fracture Toughness Data Summary.....	11

INTRODUCTION

The fracture toughness of CIP-HIP Beryllium as a function of temperature was determined using the short bar method of fracture toughness measurement⁽²⁾. Ten specimens were to be tested in the temperature range from 200°F to 500°F, inclusive. The beryllium was furnished by the Army Materials Technology Laboratory in the form of one three-point bend fracture specimen and one compact tension fracture specimen. Eight of the short bar specimens of this study were fabricated from the three-point bend specimen, and two were made from the compact tension specimen.

Previous work of Terra Tek⁽¹⁾ on the fracture toughness of beryllium has shown the short bar method of fracture toughness (K_{IcSB}) testing to be highly satisfactory and compares well with ASTM E-399 standards. K_{IcSB} measurements made at 75°F in the previous contract⁽¹⁾ yielded an average value of 10.63 MPa \sqrt{m} . This value is within the 3.1 percent standard deviation of the room temperature average value found herein, i.e. 10.96 MPa \sqrt{m} .

To perform the tests to 500°F the specimens were heated by placing a thick copper sleeve over the sample and raising the temperature with cartridge heaters placed within the sleeve. Temperature was regulated with a Love temperature controller.

TEST METHODOLOGY

Test Specimens: The short bar specimen is illustrated in Figure 1. Its

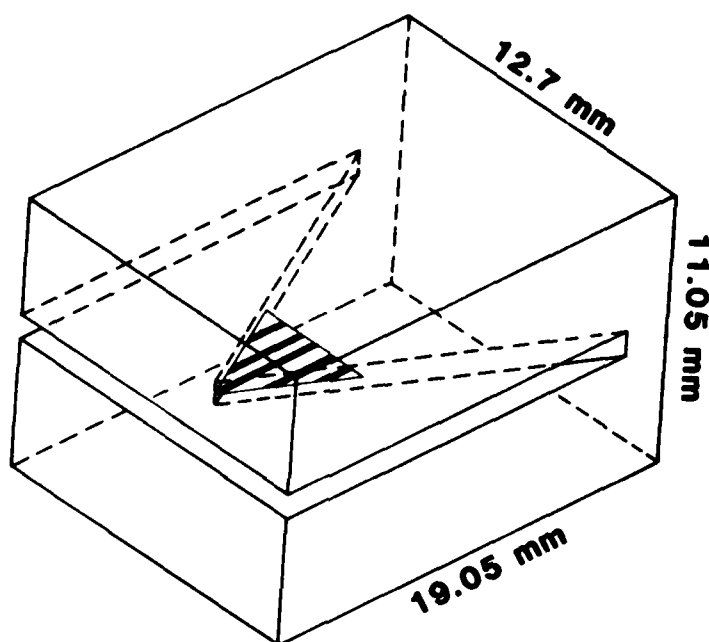


Figure 1. Short Bar Specimen.

nominal dimensions were 11.05 x 12.7 x 19.05 mm. The thickness of the chevron slot was 0.38 mm; the distance from the specimen front face to the point of the chevron slot was 6.35 mm, and the chord angle of the chevron slot was 58.0°. Figures 2 and 3 illustrate the locations in the three point bend and compact tension specimens from which the short bar specimens were taken.

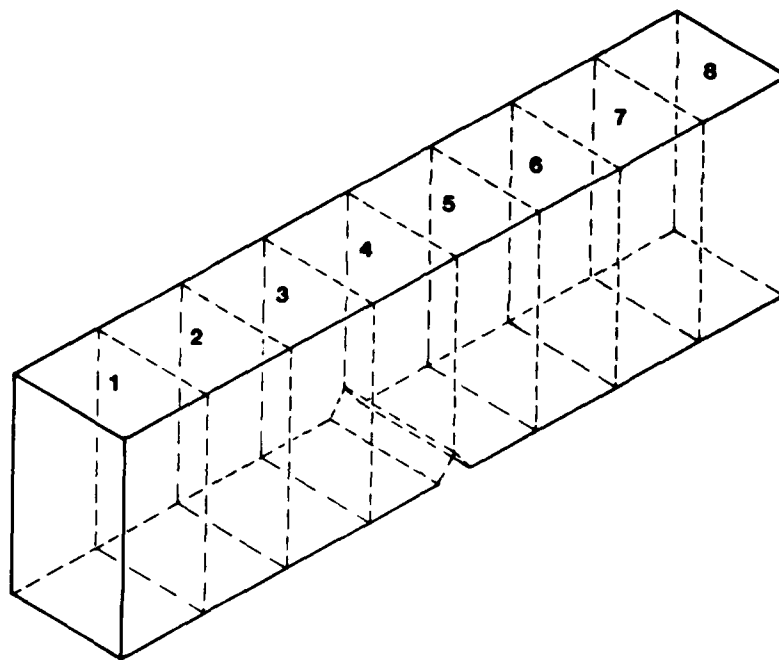


Figure 2. Short Bar Specimen Locations in the Three-Point Bend Specimen.

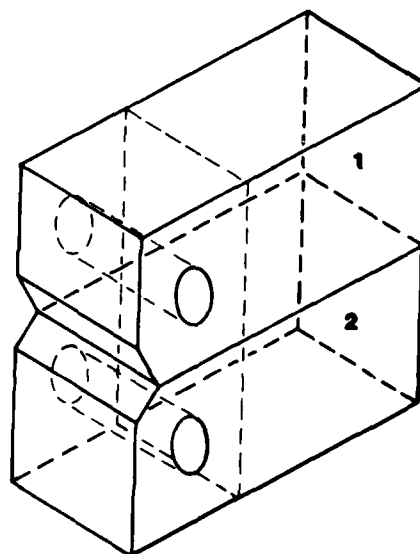


Figure 3. Short Bar Specimen Locations in the Compact Tension Specimen.

Test Method: The specimens were tested in a Fractometer I test machine. The machine makes use of a small bladder of stainless steel, called a "flatjack", to apply the mouth-opening load as shown in Figure 4a. The "flatjack" is inserted in the slot in the mouth of the specimen, and then pressurized with mercury. The pressure is transmitted to the inside surfaces of the specimen slot, forcing the specimen to open (Figure 4b), producing a crack (Figures 4b and 4c).

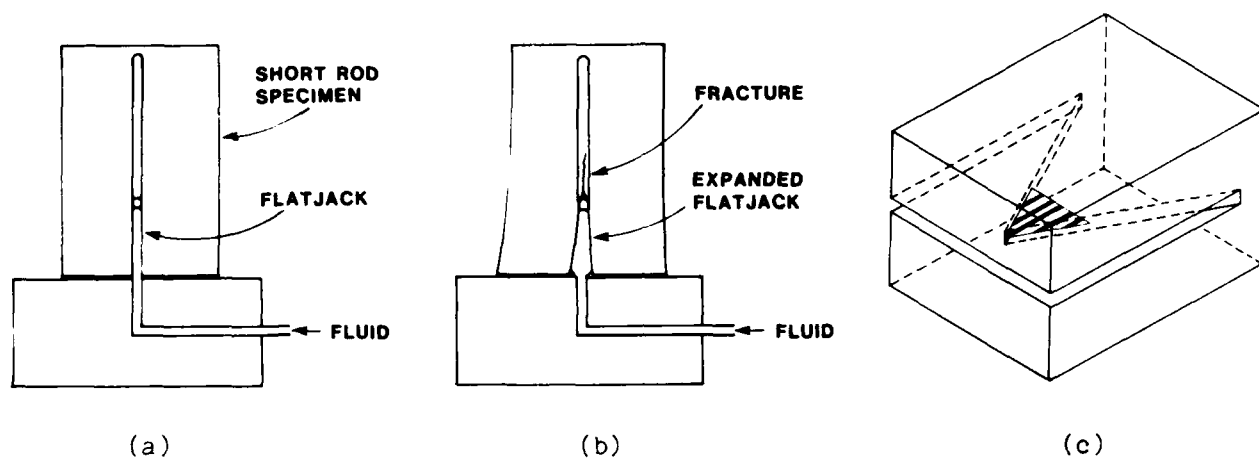


Figure 4. Fractometer method of loading short bar specimens. In (a), the specimen is seated with the flatjack in the specimen slot. In (b), fluid pressure in the flatjack is producing fracture of the specimen. The specimen deflection is greatly exaggerated. In (c), the shaded area denotes the crack.

Data Analysis: All specimens exhibited the crack jump behavior as illustrated in Figure 5. The crack would remain essentially stationary until a critical load was reached. The crack would then suddenly jump ahead to a new location with an audible "pop". It would then remain stationary again until the load was increased to a new critical value, at which point it would jump ahead again, etc. Because fracture toughness measurement is obtained from each crack jump which occurs within the central region of the specimen, some specimens provided more than one toughness measurement.

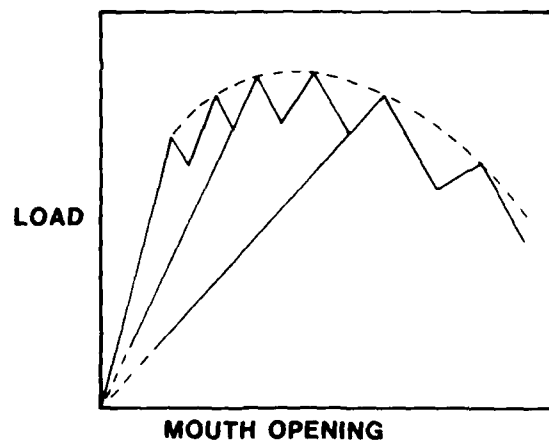
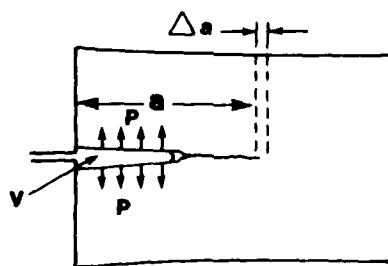


Figure 5. Load versus mouth opening type curve observed in the fracture toughness testing of beryllium using short bar specimens.

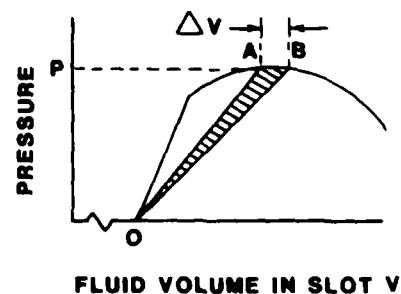
The derivation of the K_{Ic} equation for "flatjack" loading of the short bar specimen is based on linear fracture mechanics principles. The energy required to advance the steady state crack a small distance, Δa , (Figure 6a) is

$$\Delta W = G_{Ic} b \Delta a \quad (1)$$

where b is the average width of the crack from between a and $a + \Delta a$, and G_{Ic} is the critical elastic energy release rate per crack tip. The energy, ΔW , comes from the irrecoverable work done on the specimen during the test as discussed below.



(a)



(b)

Figure 6. In (a), the flatjack's loading of the specimen and incremental crack growth Δa are depicted. In (b), a plot of the pressure-volume loading curve is shown, including the straight line re-loading and unloading paths AO and BO.

Figure 6b shows a plot of the pressure-volume curve for the pressurized region of the specimen slot. During the initial loading a linear elastic path is obtained whose slope can be related to the elastic modulus of the specimen material. The onset of nonlinearity occurs when the crack initiates at the point of the "V". Suppose that the volume in the slot is increased until point A on the P-V curve is reached, corresponding to a crack length, a , in Figure 6a. If the fluid volume were then retracted from the specimen slot, the unloading path would be a straight line to the origin, since no crack growth occurs on unloading, and since the crack would close completely under the assumption of elasticity.

Now, let the specimen be loaded again. The loading path will retrace the unloading straight line OA, but when point A is reached again, further crack growth begins. Let the volume be increased beyond point A by an amount ΔV , taking the load path to point B, and causing the crack to grow an additional increment, Δa . Then let the fluid again be retracted from the specimen slot, resulting in the straight line unloading path BO. It is clear that the irrecoverable work, ΔW , done in advancing the crack the additional distance, Δa , is given by the shaded area in the triangle OAB, Figure 6b. This area is given by

$$\Delta W = \frac{1}{2} \bar{P} \cdot \Delta V \quad (2)$$

where \bar{P} is the average pressure between A and B. Letting $c_v = V/p$ be the volume compliance of the specimen. The incremental change in volume compliance in loading from A to B is

$$\Delta V = \bar{P} \Delta c_v \quad (3)$$

Using Equation (3) to eliminate ΔV from Equation (2), then

$$\Delta W = \frac{1}{2} \bar{P}^2 \Delta c_v \quad (4)$$

Eliminating ΔW by use of Equation (1) and taking the limit as Δc_v and Δa approach zero,

$$G_{Ic} = \frac{P^2}{2b} \left(\frac{dc_v}{da} \right) \quad (5)$$

Here b , P and (dc_v/da) are evaluated at the crack length, a , at which the incremental crack advance took place.

In order to cast Equation (5) in terms of the critical stress intensity factor, K_{Ic} , the plane strain equation relating G_{Ic} and K_{Ic} is used

$$G_{Ic} = K_{Ic}^2 \frac{(1-\nu^2)}{E} \quad (6)$$

where E is the elastic modulus and ν is Poisson's ratio. Thus Equation (5) becomes, after some manipulation,

$$K_{Ic} = \frac{P\sqrt{B}}{(1-\nu^2)^{1/2}} f\left(\frac{a}{B}\right) \quad (7)$$

where B is the specimen width, and

$$f\left(\frac{a}{B}\right) = \left[\frac{B}{2b} \cdot \frac{d(c_v E/B^3)}{d(a/B)} \right]^{1/2} \quad (8)$$

The quantity in brackets is a dimensionless function of the ratio a/B only. It is independent of the specimen material as long as the scaled specimen configuration remains constant.

Since the scaled crack position, a_c/B , at which the peak load is encountered is a constant⁽³⁾ (provided linear fracture mechanics conditions prevail), the value of $f(a/B)$ in Equation (7) at the time of the maximum load, P_c , is a constant, $A = f(a_c/B)$. Therefore, we have

$$K_{Ic} = A P_c \frac{\sqrt{B}}{(1-\nu^2)^{1/2}} \quad (9)$$

or simply

$$K_{Ic} = AP_c \sqrt{B} \quad (10)$$

if $(1-v^2)^{1/2}$ is approximated by unity. Calibration experiments have evaluated A for the short bar configuration in use⁽⁴⁾. They give

$$A = 7.2 \pm 0.4 \quad (11)$$

Test Results: A total of nineteen fracture toughness values were obtained from the ten specimens tested. The individual measurements are presented in Table I and plotted in Figure 7.

Table I
Individual Beryllium Fracture Toughness Measurements

Specimen Number	Temperature (°F)	K_{IcSB} (MPa \sqrt{m})	Remarks
1	300	9.35	Questionable validity due to large pop-in.
2	200	10.82	3% correction applied for poor crack guidance.*
	200	10.64	
	200	10.66	
3	300	11.88	3% correction applied for poor crack guidance.*
4	200	10.30	
5	140	11.22	
	300	11.62	3% correction applied for poor crack guidance.*
	300	10.92	
6	400	10.52	
7	156	11.37	3% correction applied for poor crack guidance.*
	400	12.16	
8	150	11.54	
	500	18.28	
9	70	10.76	
	70	10.76	
	500	15.07	
10	90	11.35	
	460	13.86	

*See text for explanation.

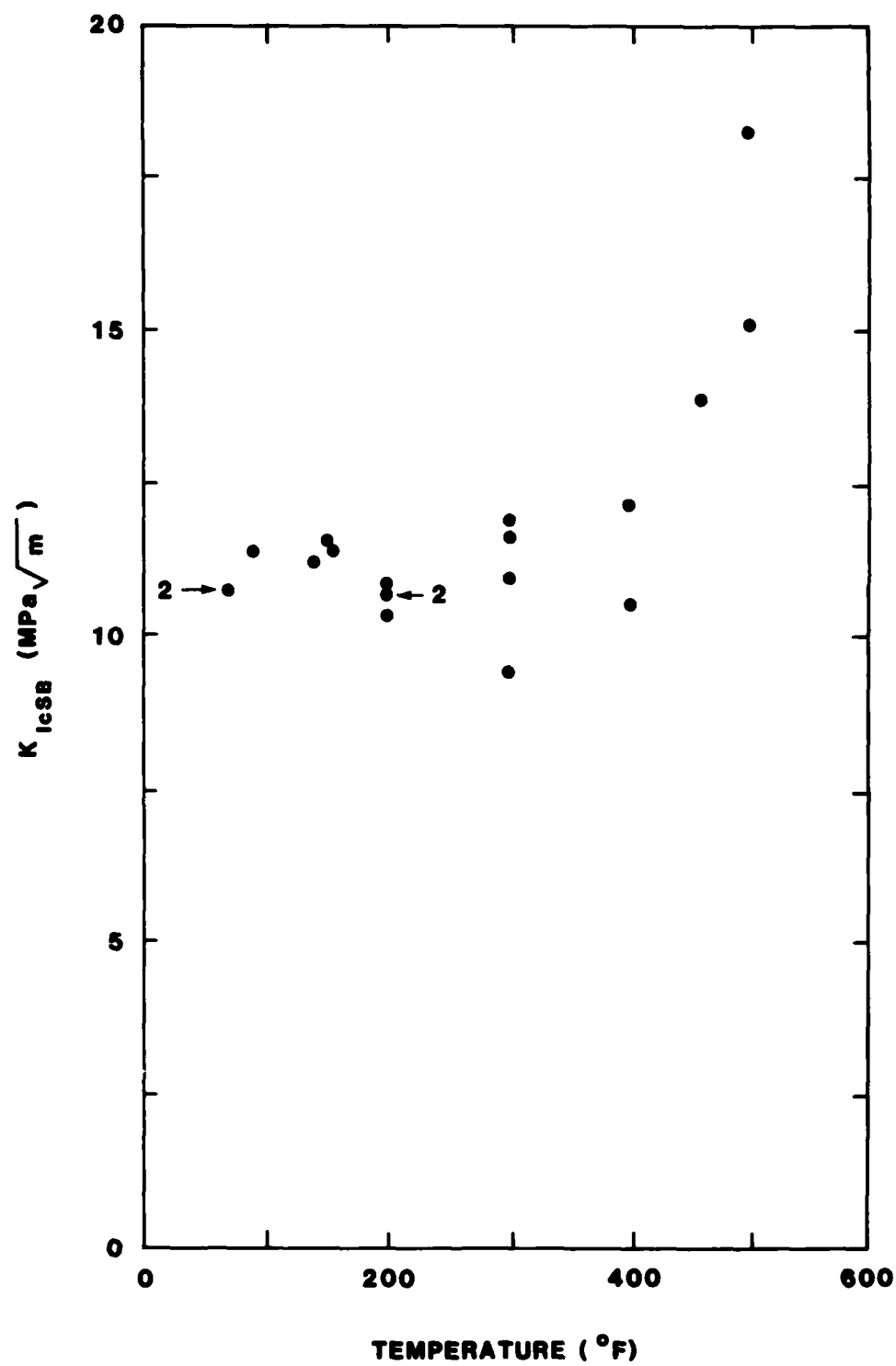


Figure 7. Beryllium Fracture Toughness. Multiple data points are indicated in the figures by numbers.

As indicated in Table I, the measurement with Specimen No. 1 is less accurate than normal because the initial crack "pop-in" (which provides no toughness measurement) carried the crack all the way through the desired toughness measurement region. The arrest point, slightly beyond the desired region, provided the measurement shown in the table, which can be considered accurate to within about five percent.

Post-test examination of the specimens showed the crack did not follow the plane of the slots very well in Specimen Nos. 2, 5 and 7. The additional crack surface area which is created when the crack curves away from the plane of the slots causes the indicated toughness to be somewhat too large. Based on testing experience, a three percent correction was estimated for each of these specimens as indicated in Table I.

It was observed that the crack jump distances tended to increase with increasing temperature. Thus, at 300°F, the initial "pop-in" almost precluded obtaining data from Specimen No. 1. Therefore, on the other tests at 300°F and above, the crack initiation and the jumps into the desired location were performed at a much lower temperature. Some of these crack jumps provided data points themselves, hence the additional data below 200°F.

DISCUSSION OF RESULTS

The data, summarized in Table II, show the K_{IcSB} for beryllium at room temperature to be 10.96 MPa \sqrt{m} . There is little increase in the fracture toughness to 400°F. Above 400°F the fracture toughness increases rapidly, increasing to a value of 16.7 MPa \sqrt{m} at 500°F.

Table II
Beryllium Fracture Toughness Data Summary

Temperature (°F)	No. of Readings	K_{IcSB} (MPa \sqrt{m})	% Standard Deviation
75	3	10.96	3.1
150	3	11.38	1.4
200	4	10.61	2.1
300	4	11.00	10.0
400	2	11.30	10.0
450	1	13.90	--
500	2	16.70	14.0

Table II shows that data scatter tended to increase with temperature as the crack "pop-in" carried the crack beyond the desired toughness measurement region. This problem did generate more data scatter than in materials with smooth crack growth behavior. While the scatter reduces the certainty of any particular value being the true toughness of the material, Terra Tek's extensive experience using the short bar testing method has shown a close correlation (within a few percent) with the results obtained by the ASTM standard method. The average values listed in Table II, therefore, are reasonable fracture toughness values for beryllium.

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